

Bounding the $Z'tc$ coupling from $D^0 - \overline{D^0}$ mixing and single top production at the ILC

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Abstract. In the present work the $Z'tc$ coupling is bounded by using the current experimental data on the $D^0 - \overline{D^0}$ meson mixing system. It is found that the strength associated to this coupling is less than 5.75×10^{-2} . The single top production through the $e^+e^- \rightarrow Z' \rightarrow tc$ process at the Z' boson resonance is studied and we found that around 10^7 tc events will be expected at the International Linear Collider. For the $Z' \rightarrow tc$ decay, we predict a branching ratio of 10^{-2} .

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1. Introduction

Many extensions of the Standard Model (SM) predict the existence of an extra $U'(1)$ gauge symmetry group and its associated Z' boson which has been object of extensive phenomenological studies [1, 2, 3]. This boson can induce flavor changing neutral currents (FCNC) at the tree level through $Z'q_i q_j$ couplings where q_i and q_j are up or down-type quarks. Due to the large top quark mass, it is commonly believed that the top quark physics could show up a window for research on new physics effects beyond the SM [4], FCNC mediated by a Z' neutral gauge boson in particular. The FCNC couplings of the top quark that are susceptible of being observed have been examined within the context of extended models [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. The simplest extended model that predicts an extra neutral gauge boson, identified as Z' , is based on the $SU_L(2) \times U_Y(1) \times U'(1)$ extended electroweak gauge group, which after spontaneous symmetry breaking (SSB) generates a mixing between the Z and Z' neutral gauge bosons [5]. Nevertheless, from electroweak precision data, it has been established that the corresponding mixing angle is strongly suppressed [3, 5]. The FCNC couplings have been studied within the context of non-universality, where it is assumed that the strength in the flavor diagonal couplings differs in the third family [6, 7, 9, 10, 11, 12]. A numerical simulation study through the $pp \rightarrow tZ'$ processes considering a signal yield of 10 events for an integrated luminosity of 100 fb^{-1} was performed at LHC scenario [12], in which the $Z'tc$ and $Z'tu$ couplings strength were found to be of orders of 10^{-2} and 10^{-3} , respectively. On the other hand, the single top production through the $pp \rightarrow tc$ and $e^+e^- \rightarrow tc$ reactions, was studied at the LHC and ILC, respectively [6]. In this work the strength of $Z'cu$ coupling was bounded from $D^0 - \overline{D^0}$ mixing. In the same context of non-universality, in Ref. [7] the top quark FCNC couplings through Z' exchange at the LHC and CLIC are studied to calculate the single top FCNC production cross section in the $pp \rightarrow tcX$ and $e^+e^- \rightarrow Z' \rightarrow tc$ processes, respectively.

The flavor-violating parameters must fulfill FCNC experimental constraints. Some models such as the left-right symmetric model or the $SO(10)$ grand unification model predict that the down-type quark transitions are strongly suppressed, while the up-type quark transitions can be as large as the U_{ts} CKM element. Particularly, the strength of the $Z'tu$ coupling is comparable to the U_{ub} element [10]. Some studies on $t \rightarrow c$ flavor-changing transitions assume that they could manifest themselves as a rare top quark decays. These type of transitions do not produce constraints on $Z'tc$ couplings since the Z' boson is required to be heavier than the top quark, provided the virtual Z' effects are not taken into account. In contrast, if we focus on the Z' virtual effects we may analyze the impact of the FCNC through the single top quark production.

In this work, the $Z'tu_i$ ($u_i = u, c$) FCNC couplings are studied. We use the mass difference ΔM_D of the $D^0 - \overline{D^0}$ mixing observed by the Babar [16] and Belle [17] collaborations to bound the strength of these couplings. To accomplish this task, it is necessary to take into account contributions arising from diagrams at the tree and one-loop level. As we shall see, the dominant contribution for the $Z'tc$ coupling

comes from the tree level diagram, implying a stronger constraint than the resulting one from the one-loop calculation. For the $Z' \rightarrow q_i q_j$ process, with $q_i, q_j = u, c, t$, the general renormalizable FCNC couplings coming from the model based on the $SU_L(2) \times U_Y(1) \times U'(1)$ gauge group are used. We restrict ourselves to the aforementioned couplings, since our objective is to compute the tc production rate mediated by a Z' gauge boson at the ILC. Instead of using the x parameter of non-universality [6, 7] to express the strength of the FCNC couplings in terms of it, we treat the strength of these couplings as a parameters to be determined in the spirit of a model-independent approach. In this way, it leads to results such that the only free parameter is the Z' boson mass; this allows us to express the strength of the coupling as a function of the Z' mass boson. Then we calculate the cross section associated with the $e^+ e^- \rightarrow tc$ reaction mediated by a Z' gauge boson at the ILC scenario and estimate the branching ratio for the $Z' \rightarrow tc$ decay process. An outline of this work is as follows. In section 2, we briefly present the theoretical frame of work for the model used. In section 3, we calculate the $Z' q_i q_j$ couplings from the $D^0 - \overline{D^0}$ meson mixing system. In section 4, we compute the $e^+ e^- \rightarrow tc$ FCNC process at the tree level by using the constraint on the $Z'tc$ coupling and estimate the branching ratio for $Z' \rightarrow tc$ decay. In section 5, we discuss our results.

2. The $Z'tu_i$ couplings

The FCNC Lagrangian contained in the simplest extended model based on the $SU_C(3) \times SU_L(2) \times U_Y(1) \times U'(1)$ electroweak gauge group [18, 19] is given by

$$\mathcal{L}_{NC} = -e J_{EM}^\mu A_\mu - g_1 J_1^\mu Z_{\mu,1} - g_2 J_2^\mu Z_{\mu,2}, \quad (1)$$

where e is the electromagnetic coupling, J_{EM}^μ is the electromagnetic neutral current, g_1 is the gauge coupling of the SM, J_1^μ is the weak neutral current of the SM, g_2 is the gauge coupling of the $U'(1)$ group and J_2^μ represents the new weak neutral current given as

$$J_2^\mu = \sum_{i,j} \overline{\psi'_i} \gamma^\mu (\epsilon_{Lij}^\psi P_L + \epsilon_{Rij}^\psi P_R) \psi'_j, \quad (2)$$

where $\epsilon_{L,Rij}^\psi$ are the chiral couplings of Z_2 with i, j running over all leptons and quarks, ψ'_i represents a fermion in the gauge interaction basis, and $P_{L,R} = \frac{1}{2}(1 \pm \gamma_5)$ are the chiral projectors. Since the interaction between the bosons Z_1 and Z_2 is too weak to be considered, we suppose no mixing between them, consequently their mass eigenstates are Z^0 and Z' , respectively [3, 5]. Since we are interested in the flavor-violating tc production rate, we consider the $\epsilon_{L,Rij}^u$ matrix for the up quark sector. Some models assume this matrix as flavor diagonal and non-universal, where the simplest treatment is the one in which the third element ϵ_{tt}^u is different [6, 7, 20]. In this work we also assume a $\epsilon_{L,R}^u$ matrix with the same properties. The FCNC couplings $\epsilon_{R,L}^u$, which are in the gauge eigenstates basis, are transformed into the mass eigenstates ones by diagonalizing the mass matrix in the Yukawa sector [18, 19]. Therefore, the FCNC couplings in the

mass eigenstates basis (Ω_L, Ω_R) can be read off as

$$\begin{aligned}\Omega_{Lij} &= g_2 (V_L \epsilon_L^u V_L^\dagger)_{ij}, \\ \Omega_{Rij} &= g_2 (V_R \epsilon_R^u V_R^\dagger)_{ij},\end{aligned}\quad (3)$$

where $V_{L,R}$ are the unitary matrices that diagonalize the mass matrix in the Yukawa sector of the SM. The up quark current given by equation (2) is transformed into the mass eigenstates basis as

$$J^\mu = \sum_{i,j} \bar{u}_i \gamma^\mu (\Omega_{Lij} P_L + \Omega_{Rij} P_R) u_j, \quad (4)$$

where $u_i = u, c, t$. This current allows us to study the FCNC transitions $Z'tu_i$, which are given by the strength of the Ω_{L,Rtu_i} matrices.

3. Bounding the $Z'tc$ couplings from $D^0 - \overline{D^0}$

Our main concern in this section is to bound the strength of the $Z'q_i q_j$ ($i \neq j$) coupling. To carry out this task we resort to the experimental result for the $D^0 - \overline{D^0}$ meson-mixing system [16, 17]. According to equations (1) and (4), the part of the Lagrangian containing the relevant information is

$$\begin{aligned}\mathcal{L}_{NC}^{Z'q_i q_j} &= -[\bar{u} \gamma^\mu (\Omega_{Luc} P_L + \Omega_{Ruc} P_R) c + \bar{c} \gamma^\mu (\Omega_{Lcu} P_L + \Omega_{Rcu} P_R) u \\ &\quad + \bar{u} \gamma^\mu (\Omega_{Lut} P_L + \Omega_{Rut} P_R) t + \bar{t} \gamma^\mu (\Omega_{Ltu} P_L + \Omega_{Rtu} P_R) u \\ &\quad + \bar{c} \gamma^\mu (\Omega_{Lct} P_L + \Omega_{Rct} P_R) t + \bar{t} \gamma^\mu (\Omega_{Ltc} P_L + \Omega_{Rtc} P_R) c] Z'_\mu.\end{aligned}\quad (5)$$

It is easy to see, from the unitary property of the $V_{L,R}$ matrices, that

$$|\Omega_{uc}| \approx |\Omega_{ut}\Omega_{ct}|, \quad (6)$$

provided that $\epsilon_{tt} \ll 1$ and $|V_{L,Rq_i q_j}| \ll 1$ for $i \neq j$. Since we focus only on bounding the strength of the coupling $Z'q_i q_j$, regardless of the possible CP-violating effects, we assume for simplicity that the different Ω 's are real, $\Omega_{L,Rq_i q_j} = \Omega_{L,Rq_j q_i}$ and $\Omega_{Lq_i q_j} = \Omega_{Rq_i q_j} \equiv \Omega_{q_i q_j}$. To constraint the $|\Omega_{tc}|$ parameter, it is necessary to take into account the short-distance effects which are included in the tree-level and box diagrams shown in figure 1. Because the amplitudes are dominated by the Z' gauge boson and top quark masses, we may neglect the external momenta (heavy mass limit). In this approximation, the tree-level amplitude can be written as

$$\mathcal{M}_{\text{tree}} = -\frac{i\Omega_{uc}^2}{m_{Z'}^2} \bar{u} \gamma^\alpha c \bar{u} \gamma_\alpha c, \quad (7)$$

where $m_{Z'}$ is the mass of the Z' gauge boson. The $\mathcal{M}_{\text{tree}}$ amplitude is related to a four-quark effective interaction given by the effective Lagrangian:

$$\mathcal{L}_{\text{eff}}^{\text{tree}} = -\frac{\Omega_{uc}^2}{4m_{Z'}^2} (Q_1 + 2Q_2 + Q_6), \quad (8)$$

where a $1/4$ factor has been introduced to compensate two Wick contractions. The various Q_i in equation (8) are dimension 6 effective operators used in the literature [21, 22].

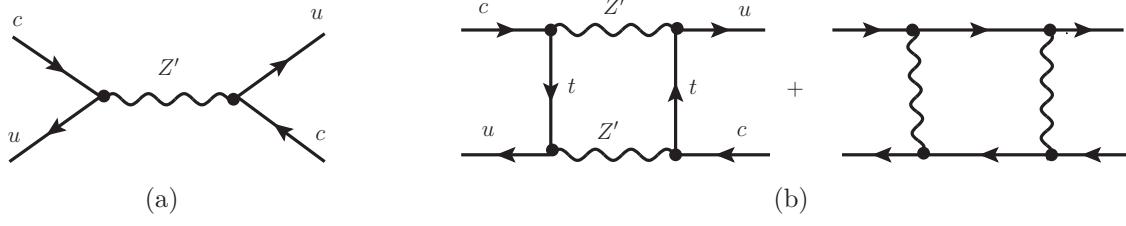


Figure 1. (a) Tree diagram (b) Box diagrams for $D^0 - \bar{D}^0$ mixing.

Analogously, the one-loop level amplitude is given by:

$$\mathcal{M}_{\text{box}} = 2 \Omega_{tu}^2 \Omega_{tc}^2 \int \frac{d^4 k}{(2\pi)^4} \frac{[\bar{u} \gamma^\lambda (\not{k} + m_t) \gamma^\nu c] [\bar{u} \gamma_\nu (\not{k} + m_t) \gamma_\lambda c]}{(k^2 - m_t^2)^2 (k^2 - m_{Z'}^2)^2}, \quad (9)$$

where m_t denotes the mass of the top quark. After some algebra we arrive at the following result:

$$\begin{aligned} \mathcal{M}_{\text{box}} = & -\frac{i}{16\pi^2} \frac{\Omega_{tu}^2 \Omega_{tc}^2}{m_t^2} \left[f(x) \bar{u} \gamma^\lambda \gamma^\alpha \gamma^\nu c \bar{u} \gamma_\nu \gamma_\alpha \gamma_\lambda c \right. \\ & \left. + g(x) \bar{u} \gamma^\lambda \gamma^\nu c \bar{u} \gamma_\nu \gamma_\lambda c \right], \end{aligned} \quad (10)$$

where $f(x)$ and $g(x)$ are loop functions given as

$$f(x) = \frac{1}{2} \frac{1}{(1-x)^3} [1 - x^2 + 2x \log x], \quad (11)$$

$$g(x) = \frac{2}{(1-x)^3} [2(1-x) + (1+x) \log x]. \quad (12)$$

with $x = m_{Z'}^2/m_t^2$.

The \mathcal{M}_{box} amplitude is related to a four-quark effective interaction given by the effective Lagrangian:

$$\begin{aligned} \mathcal{L}_{\text{eff}}^{\text{box}} = & -\frac{\Omega_{tu}^2 \Omega_{tc}^2}{64\pi^2 m_t^2} [f(x) (4Q_1 + 32Q_2 + 4Q_6) \\ & + g(x) (8Q_3 + 4Q_4 + Q_5 + 4Q_7 + Q_8)], \end{aligned} \quad (13)$$

again a 1/4 factor has been introduced to compensate two Wick contractions. On the other hand, the mass difference ΔM_D provided by the $D^0 - \bar{D}^0$ meson-mixing system is given by

$$\Delta M_D = \frac{1}{M_D} \text{Re} \langle \bar{D}^0 | \mathcal{H}_{\text{eff}} | D^0 \rangle, \quad (14)$$

where \mathcal{H}_{eff} is the effective Hamiltonian and M_D is the D^0 meson mass. Here, the effective Lagrangian is obtained by adding the tree-level and box contributions: $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{eff}}^{\text{tree}} + \mathcal{L}_{\text{eff}}^{\text{box}}$. Therefore, by using the modified vacuum saturation approximation [21] we have:

$$\Delta M_D = \frac{\Omega_{uc}^2}{4m_{Z'}^2} \left[\langle Q_1 \rangle + 2\langle Q_2 \rangle + \langle Q_6 \rangle + \frac{x}{16\pi^2} (f(x)(4\langle Q_1 \rangle + 32\langle Q_2 \rangle \right.$$

$$\begin{aligned}
& + 4\langle Q_6 \rangle) + g(x) (8\langle Q_3 \rangle + 4\langle Q_4 \rangle + Q_5 + 4\langle Q_7 \rangle + \langle Q_8 \rangle) \Big] \\
& = \frac{1}{12} \frac{\Omega_{uc}^2}{m_{Z'}^2} f_D^2 M_D B_D \left[1 + \frac{x}{8\pi^2} (32f(x) - 5g(x)) \right], \tag{15}
\end{aligned}$$

where we have used the relation given by equation (6), B_D is the bag model parameter and f_D represents the D^0 meson decay constant. We can see from equations (8), (13) and (15) that the main contribution to ΔM_D comes from the tree-level amplitude while the contribution coming from the box amplitude is of approximately 17%-19% in the range of $800 \text{ GeV} \leq m_{Z'} \leq 3000 \text{ GeV}$.

In order to compute the strength of the couplings we take $B_D \sim 1$, $f_D = 222.6 \text{ MeV}$ [23] and $M_D = 1.8646 \text{ GeV}$ [24]. Considering that ΔM_D does not exceed the experimental uncertainty [16, 17, 25], the bound is

$$|\Omega_{uc}| < \frac{3.6 \times 10^{-7} m_{Z'} \text{ GeV}^{-1}}{\sqrt{1 + \frac{x}{8\pi^2} (32f(x) - 5g(x))}}, \tag{16}$$

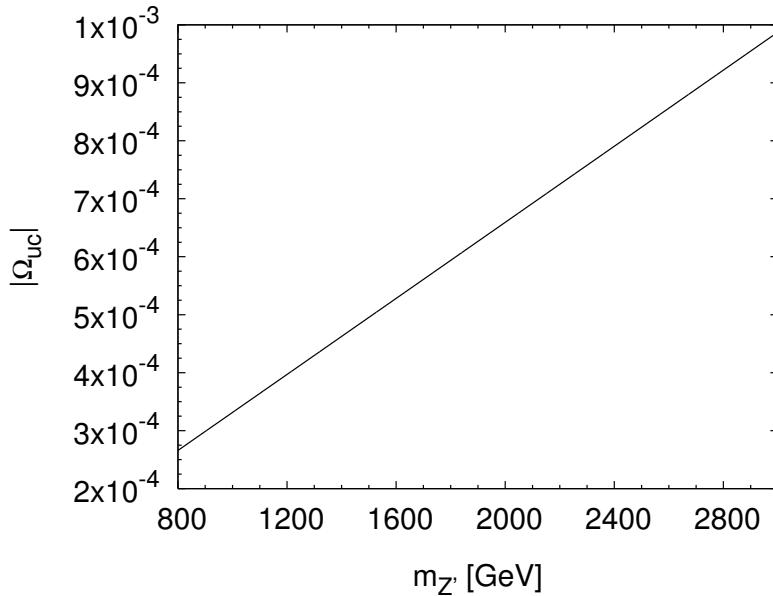


Figure 2. Behavior of $|\Omega_{uc}|$ coupling as a function of Z' boson mass.

In figure 2, we depict the behavior of maximum of $|\Omega_{uc}|$ as a function of the Z' boson mass. It can be observed that the growth is not bigger than one order of magnitude in a broad range of the mass.

Since we are interested in bounding the Ω_{tc} coupling, we take the relation previously found: $|\Omega_{uc}| \approx |\Omega_{tc}\Omega_{tu}|$. For $m_{Z'} = 1 \text{ TeV}$, we obtain a bound $|\Omega_{tc}\Omega_{tu}| < 3.31 \times 10^{-4}$, moreover, if we assume that $\Omega_{tc} = 10\Omega_{tu}$, as it occurs for the absolute values of U_{ts}, U_{td} elements in the CKM matrix [24], we found that $|\Omega_{tc}| < 5.75 \times 10^{-2}$ and $|\Omega_{tu}| < 5.75 \times 10^{-3}$, which are of the same order of magnitude than those obtained in [6, 10]. Let us emphasize that our bound on $Z'tc$ coupling was calculated by using experimental results on the $D^0 - \overline{D^0}$ meson-mixing system. We can also mention that the

Table 1. The strength of the flavor-diagonal $Z'f\bar{f}$ couplings.

	Sequential Z	E_6	Average
Q_L^u	0.3456	$\frac{1}{\sqrt{24}}$	0.2749
Q_R^u	-0.1544	$\frac{-1}{\sqrt{24}}$	-0.1793
Q_L^d	-0.4228	$\frac{1}{\sqrt{24}}$	-0.1093
Q_R^d	0.0772	$\frac{-1}{\sqrt{24}}$	-0.0635
Q_L^e	-0.2684	$\frac{1}{\sqrt{24}}$	-0.0321
Q_R^e	0.2316	$\frac{-1}{\sqrt{24}}$	0.0137
Q_L^ν	0.5	$\frac{1}{\sqrt{24}}$	0.3521

value $\Omega_{tc} = 10 \Omega_{tu}$ taken to bound the $Z'tc$ coupling strength is equivalent to the value assumed of few tenths for the x parameter of non-universality in other approaches [6, 7]; however, our assumption is inspired by physical results taken from the CKM matrix.

4. The process $e^+e^- \rightarrow Z' \rightarrow tc$ at ILC collider

In previous works [6, 7, 8], the flavor-diagonal $Z'f\bar{f}$ (f being any SM fermion) couplings have been calculated, each having different strength depending on the model used. To make predictions on the process $e^+e^- \rightarrow Z' \rightarrow tc$, from those couplings, here we use the upper and the lower values provided by the sequential Z and E_6 ‡ models, respectively. The relevant parameters used to calculate the strength of the couplings are the chiral charges $Q_{L,R}^f$ taken from [6]. Rather than using the maximum and minimum values of the strength of these chiral charges, we find interesting, only for comparison proposes, to take their average; the different values for the charges are displayed in table 1. Additionally, we also use the strength of the $\Omega_{tc}\Omega_{tu}$ coupling previously determined to complete the set of parameters needed to compute the total width for the Z' boson decay.

We resort to the Breit-Wigner resonant cross section, which is

$$\sigma(e^+e^- \rightarrow Z' \rightarrow tc) = \frac{12\pi m_{Z'}^2}{s} \frac{\Gamma(Z' \rightarrow e^+e^-) \Gamma(Z' \rightarrow tc)}{(s - m_{Z'}^2)^2 + m_{Z'}^2 \Gamma_{Z'}^2} \quad (17)$$

where \sqrt{s} is the center of mass energy and $\Gamma_{Z'}$ is the Z' total decay width. On account of the total Z' width we include the total possible flavor-diagonal and a flavor-nondiagonal decay modes, namely: $\nu_e\bar{\nu}_e$, $\nu_\mu\bar{\nu}_\mu$, $\nu_\tau\bar{\nu}_\tau$, e^+e^- , $\mu^+\mu^-$, $\tau^+\tau^-$, $u\bar{u}$, $c\bar{c}$, $t\bar{t}$, $d\bar{d}$, $s\bar{s}$, $b\bar{b}$, $\bar{u}c + u\bar{c}$, and $\bar{t}c + t\bar{c}$. For the width of the $Z' \rightarrow e^+e^-$ process we have employed the results given in [6]. For the decay width $\Gamma(Z' \rightarrow tc)$, we obtain

$$\Gamma(Z' \rightarrow tc) = \frac{(2m_{Z'}^4 - m_t^4 - m_{Z'}^2 m_t^2) \Omega_{tc}^2}{12\pi m_{Z'}^3}. \quad (18)$$

In figure 3 we show the Breit-Wigner cross section for the tc flavor violation production as a function of the center-of-mass energy. For computing the cross section,

‡ Although in Ref. [6, 7] the strength parameter with the biggest values is for the Z_ψ model which is contained in a larger group E_6 , we simply have termed it as E_6 model.

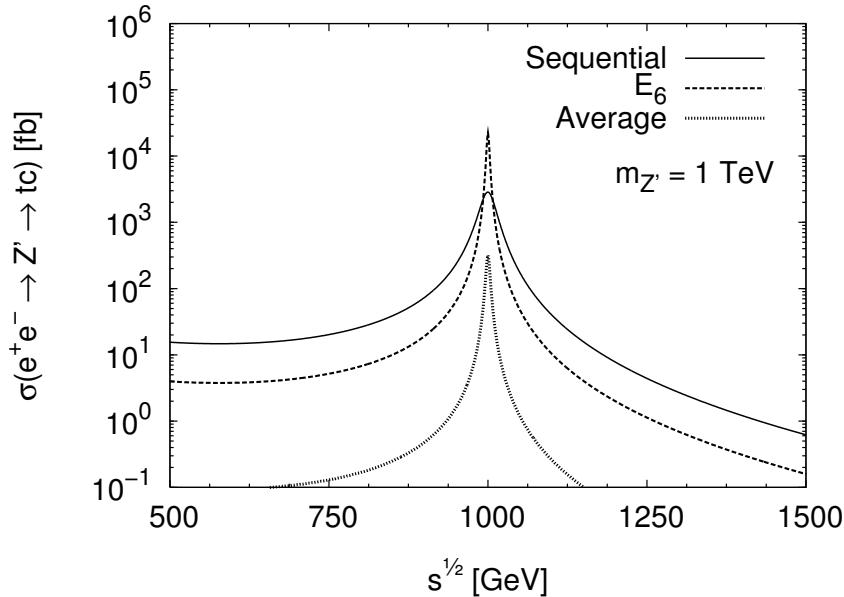


Figure 3. Cross section for $e^+e^- \rightarrow Z' \rightarrow tc$ process as a function of \sqrt{s} for $m_{Z'} = 1$ TeV.

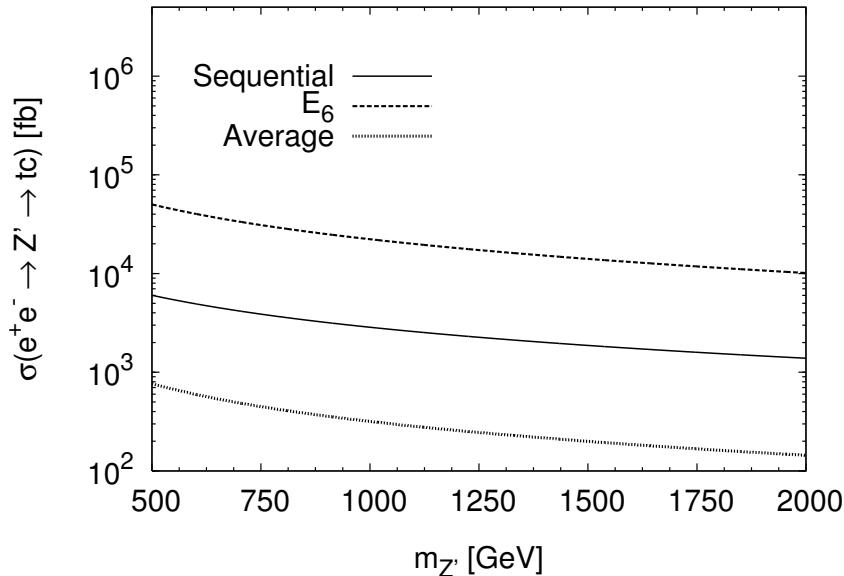


Figure 4. Cross section for $e^+e^- \rightarrow Z' \rightarrow tc$ process at the resonant values as a function of $m_{Z'}$.

we set the same value of the Ω_{tc} parameter for both analyzed models as a function of the Z' boson mass. It is expected that the ILC will operate at a luminosity of 500 fb^{-1} in the first years of running [26]. In this context, from our results shown in figure 4, we can predict around 10^7 events just at the resonance for the E_6 model, while for the sequential Z model it is expected to obtain around 10^6 events and for the average of the two models, it is expected around 10^5 events. According to our results, it is more

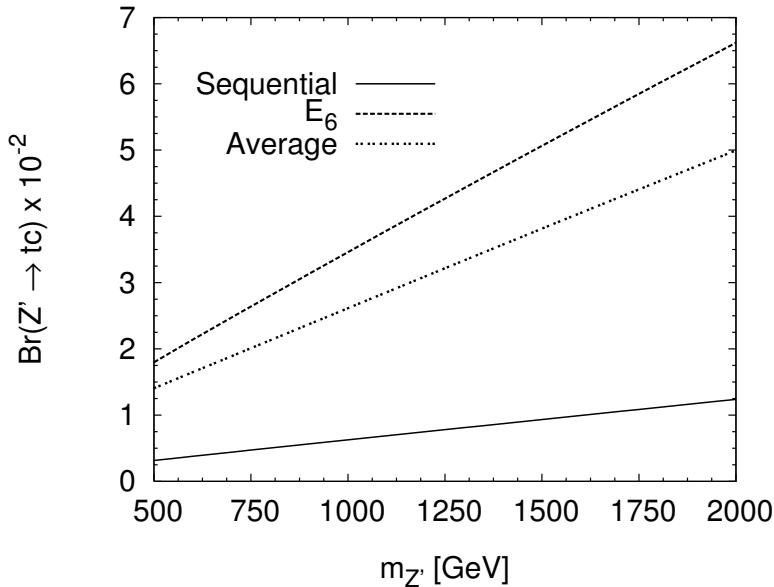


Figure 5. The branching ratio for $Z' \rightarrow tc$ decay.

feasible to observe flavor violation in the E_6 model, which is corroborated with the $Z' \rightarrow tc$ decay as it can be appreciated from figure 5. We obtain that the associated branching ratio is of the order of 10^{-2} .

It is useful to compare our results on single top quark production mediated by a Z' gauge boson with others previously obtained from different models and approaches. In the context of the LHC, for the single top quark production with flavor violation mediated by a Z' , a previous exhaustive work has developed that the capability of the LHC to detect a tc FCNC effects by measuring the production of $t\bar{c} + \bar{t}c$ pairs is much less as compared to the ILC approach [6]. So we leave aside this context and concentrate on linear colliders scenarios. First, we compare our results for the $e^+e^- \rightarrow \gamma\gamma \rightarrow tc$ cross section at the energy $\sqrt{s} = 500$ GeV (see figure 3) with that obtained in the SUSY model [27]. The supersymmetric model predicts a cross section of the order of 1 fb, which agrees with our most conservative result; however, it is one order of magnitude smaller than our prediction for the sequential Z model.

On the other hand, within the context of the ILC, at the energy of the resonance, $\sqrt{s} \sim m_{Z'} \sim 1$ TeV, our average gives around 10^5 tc events; this production is higher by four orders of magnitude than those derived from the SUSY models [15], which were calculated at energies higher than $2m_t$. In addition, the production of around 10^4 tc events calculated at the resonance within the context of the Compact Linear Collider [6, 7] can be compared with our predictions which are higher by one and three orders of magnitude for the average and the E_6 model, respectively. The discrepancy in these results can be understood if we take into account that the values for the couplings used in [6, 7], $(B^u)_{ct} = (V^\dagger \epsilon^u V)_{ct} \sim 10^{-2}$, are model dependent for both the sequential Z and the E_6 models, while the value for our coupling is model independent, $\Omega_{tc} \sim 10^{-1}$.

and it was obtained from experimental restrictions.

Within the same context of the ILC, we may also contrast our result, with the obtained previously for us [14], where the top quark production is mediated by a Higgs boson. We found that around 10^3 tc events will be produced for a Higgs mass of the order of top quark mass, which is two orders of magnitude less than the average prediction, calculated at the resonance. Moreover, we have estimated the branching ratios for the $Z' \rightarrow tc$ and $Z' \rightarrow tu$ decays calculated at the resonance, which are of the order of 10^{-2} and 10^{-4} , respectively. We can mention that these values are one order of magnitude less restrictive than the corresponding branching ratios obtained in the 3-3-1 model [8].

5. Final remarks

In this work we have studied the possible flavor violation mediated by a Z' neutral gauge boson, which is predicted by several models beyond the SM. We have bounded the strength of the flavor-violating $Z'tc$ coupling using the experimental results coming from the $D^0 - \overline{D^0}$ meson-mixing system, where our constraint depends only on the Z' boson mass. For a $m_{Z'} = 1$ TeV, we have found that the flavor-violating parameter $|\Omega_{tc}| < 5.75 \times 10^{-2}$ is in agreement with similar predictions in previous works. We have calculated the cross section for the $e^+e^- \rightarrow Z' \rightarrow tc$ process in the ILC scenario, where we found an estimation of around 10^7 events for a luminosity of 500 fb^{-1} in the context of Z' boson predicted by the E_6 model. According to our results, the tc flavor violation effect mediated by a Z' boson from the E_6 model is more favorable of being observed than that predicted in the sequential model. This behavior is also repeated for the branching ratio of the $Z' \rightarrow tc$ decay.

Acknowledgments

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